Designing a Small-Scale NWTC Drive Train for Investigation of Multiple Generator Drive Train Configurations

Serge Delak
Energy Research Undergraduate Laboratory Fellowship (ERULF) Program
Rensselaer Polytechnic Institute
National Renewable Energy Laboratory
Golden, Colorado 80401
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Participant:____
Signature

Research Advisor____
Signature

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Abstract

Recent trends toward increasingly large wind turbines are inhibited by the disproportionate cost of high-torque drive trains which are necessary for the efficient generation of power. Multiple-generator drive trains have the potential to decrease the size and cost of wind turbine drive trains by distributing high torque among several smaller generators. Although many other advantages exist, uncertainty about power sharing remains a primary concern. As a result the National Wind Technology Center (NWTC) is considering testing such a system on both its dynamometer, and on a small wind turbine. This paper documents the preliminary design, and component selection for such a test system.

In addition to testing torque sharing among generators in a multiple-generator system, such a test bed would also be used for exploration of power electronics and permanent magnet generator configurations that could be advantageous when combined in a multiple-generator system. Additionally, replacing the drive train of the NWTC's Unsteady Aerodynamics Experiment (UAE) turbine would provide an additional test bed for rotor and controls testing. For this reason the main specifications of this drive system were made based on the UAE turbine specifications.

After considering several possible generator and power electronics configurations, a system was recommended. It is comprised of 3 Moog FAST-V4-010 servo motors to be used as generators with diode rectification to a single DC bus and a single Trace 30kVA inverter. This recommended system would cost about $108,000 to build and has several advantages over the other configurations considered.

Introduction

Larger and more cost-effective turbines are of key importance in decreasing the cost gap between wind and fossil energy. As wind turbine technology has become more advanced, optimum turbine sizes have increased. For example, a few years ago, 750 kW wind turbines were argued to be the most economical, but now many agree that the most economical wind turbines are in the MW range. However, although bigger turbines decrease the unit cost of electricity, some aspects of larger turbines become less cost-effective as turbines handle more power. One such component is the gearbox and drive train.

As a turbine rotor diameter is doubled, the turbine's rated power is quadrupled (as rotor swept area is proportional to the square of diameter), thus making it advantageous to increase the rotor diameter of a wind turbine. Unfortunately, as the rotor diameter is doubled (requiring a reduction in rotational speed for optimal tip-speed ratio), the shaft torque and, therefore, the gearbox size and cost, are increased by a factor of eight. This hindrance is a major obstacle to cheaper wind power. Large gear ratio gearboxes are commonly used to take low RPM, high-torque input, and turn it into high RPM, low-torque output, which is favorable for generators. But, because these gearboxes can be expensive, alternative strategies are being considered. Although some recent research has been emphasizing systems with smaller gearboxes and generators rated for higher torque and slower speeds, these generators become large and expensive for big turbines. However, a second alternative drive train strategy with great cost-saving potential, the multiple-generator drive train system, might be a better answer to the drive train problem.

The multiple-generator drive train configuration would distribute a large-input torque among several small high-torque generators, thus decreasing the size and cost of many drive train components (as seen in figure 1).

Figure 1: Illustration of the multiple generator drive train concept. In this design six generators are all driven by the same rotor input.

Some studies have shown that such a configuration could cut drive train costs by 35-50%, and the total cost of energy by as much as 12% (Windpact, Clipper). Furthermore, small modular components can add to cost reduction by economies of scale, reduced maintenance equipment requirements (i.e. no crane rental), and fractional reduction in generation due to component failure.

Although multiple-generator drive train configurations have great potential to reduce the cost of wind energy, the idea is fairly new and uncertainties exist. The biggest uncertainty is how equally torque and power will be distributed among the various generators. As a result, the National Wind Technology Center (NWTC) is considering testing such a drive train, both on its dynamometer and on a wind turbine. In doing so, the NWTC hopes to prove that such a system can work, and that power sharing can be controlled well between all generators. Additionally, this drive train study hopes to increase our understanding of permanent magnet (PM) generators, power electronics (PE), and how they can work together in this system.

This paper documents the preliminary design of a test multiple-generator drive train system. Specifically, it documents the selection of drive train components and the configuration of those components into a system that could eventually be built and tested.

Materials and Methods

First, goals for a multiple-generator drive train test rig were considered. With the size and scope of the project known, a list of component specifications was compiled. Several generator and power electronics (PE) configurations were explored. Spreadsheets were used to roughly model potential systems and determine under what conditions a design would be feasible (generator torque and speed as a function of gear ratio and number of generators, etc.). Components were found that matched specifications by searching manufacturer's products through the use of the internet, and telephone. Some requests were made for consideration of custom-built components. With components found, a second spreadsheet model was made to determine the compatibility and performance of several systems (using tip-speed and power limited, diode rectification, and power balance assumptions). After comparing the advantages and disadvantages of the various drive train configurations (including price, availability, and ability to be used for useful research), a particular configuration was recommended.

Motivation

The main goals of a multiple-generator test bed were obtained from WindPACT (Wind Partnership for Advanced Component Technology) and NWTC (National Wind Technology Center) reports as well as verbal requests. These goals include the following:

- Investigate Torque Sharing Among Multiple Generators
- Advance Experience with Permanent Magnet (PM) Generators
- Explore New Power Electronics Configurations
- Provide a 30kW Variable Speed Turbine for Controls and Rotor Testing

Investigation of torque sharing among generators with a common rotor input is of major concern to the development of multiple-generator wind turbines. Ideally, identical generators would be able to share torque perfectly and stresses associated with uneven torque distribution would be negligible. However, the variation in manufactured electrical machines is significant enough to warrant further exploration of torque sharing among generators and control strategies for balancing generator torque loads. Vibration is also a concern associated with generator variability and gearbox construction. Stresses and energy loss due to vibration can lead to premature failure and efficiency losses.

Gaining experience with PM generators is of value not only for multiple-generator drive train development, but also for any industry that requires high torque motors and generators, especially the wind industry. Research experience with PM generators for wind applications is especially valuable at present because recent materials advances in magnets are greatly reducing the cost of permanent magnet machines. Decreasing costs will make PM machines attractive in the near future because they will become cost effective for applications that require:

- Compact, High-Torque Machines

- Low Maintenance and High Reliability (Due to their simple construction)
- Near Unity Power Factor (PF)
- High Efficiency

Just as the unique multiple-generator drive train configuration can reduce capital cost through an efficient use of materials, unique PE configurations can reduce electronics costs. The multiple-generator configuration offers the chance to explore interesting new PE opportunities, especially when combined with the decreasing cost of advanced PE.

Using IGBT type rectifiers and inverters (dual IGBT) in parallel (one set per generator) is a potentially useful configuration. An independently controlled DC bus between the rectifier and inverter provides a mechanism for extremely good torque control for both optimizing rotor dynamics and controlling torque sharing. Additionally, IGBT type inverters can provide superior power quality (low distortion and power factor control). Running the rectifiers in passive mode (on a custom system) would essentially allow the testing of a diode rectification configuration with no rewiring. This dual IGBT configuration seems advantageous for industry because it is a practical way of combining power limited IGBTs (which become impractical above the 1MVA rating) into multi-MW turbines.

While the dual IGBT configuration provides excellent control, a diode bridge rectifier can significantly reduce the cost of power electronics because diode technology is a fraction of the cost of more sophisticated PE. In this configuration, the rectifier has no capability of being controlled, and the DC bus voltage varies proportionally to the generator voltage (V_{DC} = m*sqrt(2)*V_{LL}, where 'm' is any integer and nominally 2). As a result, the inverter must be capable of handling a larger range of voltages and has much more limited control of generator torque, and practically no control on torque sharing. For this reason it would be an excellent configuration to research. Mechanically separating the phases of the various 3 phase generators would essentially provide 'n' phase voltage where 'n' is the number of generators multiplied by 3. The resulting DC voltage would be much "cleaner" and have less ripple, thus allowing for less robust power conditioning equipment (capacitors). PE components separated by a DC bus might also lead to savings by locating the inverter on the ground. This would cut cabling costs and power losses due to the skin effect. Additionally a DC chopper could be added for each generator to better control torque if needed, and DC voltage could easily be boosted by integer values based on diode/capacitor voltage multiplier configurations (as shown by 'm' in previous equation). The common DC bus could then be inverted through one large inverter. Although an IGBT type inverter would be preferred, a sophisticated SCR (such as a GTO) might be tried because unlike IGBTs they can be cost effective at the multi-MW level. An additional configuration might run each generator's GTO inverter in parallel and combine signals to produce high quality grid power.

Although the prime motivation for developing a new multi-generator drive train is to research torque sharing, permanent magnet generators, and power electronics, there is additional motivation in that building a turbine with this drive train would be useful in doing other NWTC research including controls and rotor research. The direct results of these desires are the drive train specifications, many of which match the specifications for the Unsteady Aerodynamics Experiment (UAE) turbine. Replacing the UAE turbine drive train with a multiple-generator drive train would provide a turbine for testing many new concepts. The nominal rotor speed (72 RPM) and rotor diameter (10m) would be kept the same as on the UAE, but the number of generators, gear ratio, maximum RPM and drive type (variable speed rather than constant) would change.

Results

With the preliminary specifications (nominal and maximum power and RPM) for the generators, the required torque was calculated for different drive train gear ratios and number of generators using mechanical power balance formulas (Power =Torque * Rotational Speed). The following figure graphically shows the results.

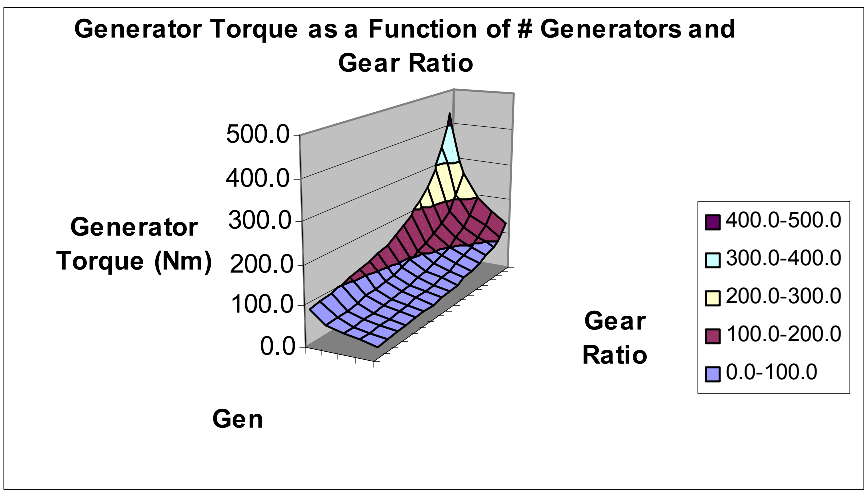

Figure 2: Generator torque as a function of gear ratio and number of generators. The number of generators and power ratings of each are approximated to be integer values for a system near 25kW.

With torque, speed, and power ratings, manufacturers were searched for PM generators or motors that fit such requirements. Several companies were contacted for custom-built generators. Due to the limited availability of off the shelf PM generators, and the desire to keep the number of generators low (2-3) for simplicity, most of the usable generators were rated around 10kW. Thus the design became focused on a three generator system. The following table presents the generators found to match specifications.

Table 1: Available PM Generators and Nominal Specifications

Generator	Power (kW)	Speed (RPM)	Torque (Nm)	Poles	Price/ Gen
Bergey Excel-S	10	310	308	38	$5000 - $7000
Moog FAST-V4-010 Servomotor	18	1000	172	8	$15,000
UQM Custom Built	10	720	133	NA	>$50,000
GD Electric Boat Custom Built	10	720	133	NA	NA

Power electronics manufacturers were searched for either 10 kVA rectifier/inverter units (one for each generator) or 30 kVA inverters (to invert all the system output). The following matches were found to be applicable.

Table 2: Available PE and Specifications

Company	Rating	Input	Output	Price
UQM custom	10kVA	3-phase, ~750Vac max	3-phase, 480Vac	Custom
Bergey/ Trace	10kVA	3-phase, 350Vac max	1-phase, 240Vac	$7,400
Trace	10kVA	330-600Vdc	3-phase, 208Vac	$8,473
Trace	30kVA	330-600Vdc	3-phase, 208Vac	$21,000
AES	30kVA	300-600Vdc	3-phase, 208Vac	$22,000

After generator and PE components were found, their specifications could be compared to analyze the feasibility of systems.

The 3 UQM modules (each comprised of a generator and dual IGBT configuration, see below) were to be custom built at a cost of at least $150,000 total. Because cheaper alternatives were found, this configuration was not considered further. Additionally, the 3 dual IGBT module configuration was not preferred because it would not test the diode rectification option.

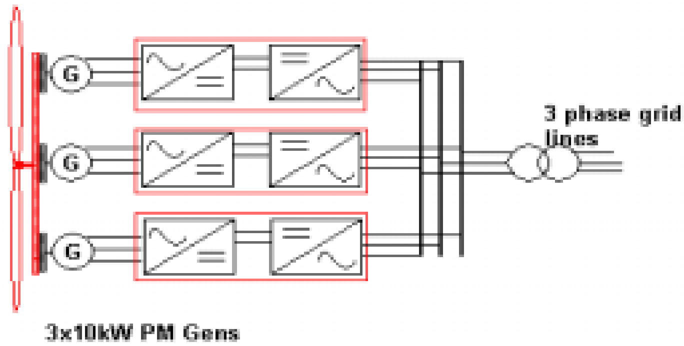

Figure 3: Drive Train Configuration Option with Three Independent Power Processor Units (One Per Generator) which output 3 Phase AC

Using the Bergey generators with matching Bergey/Trace power processors in parallel would essentially provide the same system as the UQM system previously described. However, although this system would also not test the diode rectification option, it is of interest because it is the cheapest to build, at a cost of $44,000 for PE and generators. The GridTek Bergey/Trace power processor outputs 1-phase output for a grid-connected household system, but because the 3 independent units would be used, 3-phase output is essentially achievable (see below). In order to match the nominal generator torque with the rotor input torque, and match the generator output voltage with power processor input voltage, a gear ratio of 3:1 would have to be used.

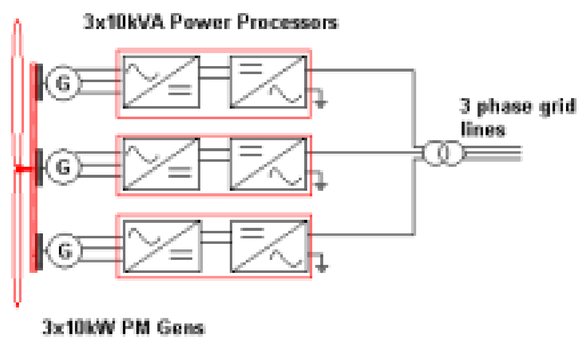

Figure 4: Drive Train Configuration Option with Three Independent Power Processor Units (One Per Generator) which output 1 Phase AC

A third system with three paralleled PE modules was considered as well. It was the same configuration as shown in Figure 3, but with Moog servo motors as generators, diode rectifiers, and Trace 10kVA inverters. This system would lack sophisticated rotor torque control, but independence between the generator modules would allow for better torque sharing control. This system would be interesting to test because of the uncertainty and cost-effectiveness associated with the diode rectification. Because IGBT ratings are not expected to surpass 1MVA, such a system might provide useful information for high-torque, multi-MW turbines with IGBT PE. In this project's test configuration, a 5.25 gear ratio would need to be used to match torque and voltage requirements, and the cost of the PE and generators would be $71,000.

Systems with diode rectification to a common DC, and one 30kVA inverter were also considered (see below). Because both 30kVA inverters had almost identical specifications and prices, they were considered to be comparable. This configuration would have the advantage of testing diode rectification control issues, and being a likely candidate for commercial application.

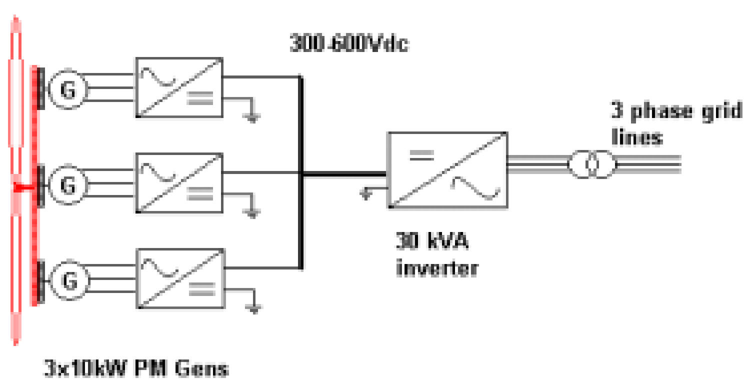

Figure 5: Drive Train Configuration Option with 3 Diode Rectifiers (One Per Generator), and a common 30 kVA inverter

The option of using the 10kW Bergey generators with either of the 30kVA inverters was found not to work well. This was because the gear ratio required to keep the generators within their torque limits made the generators spin too fast and produce a voltage too high for the inverters. To keep the generators from spinning too fast and producing a high voltage, the gear ratio could be decreased, and more generators used. Although this system would work, the additional generators would make the system more complicated than desired. Although it may be possible to reduce the DC voltage (‘m’ = 1) using an alternative diode bridge configuration, this solution was not considered because the resulting DC quality might not be acceptable for the inverter.

The option of using Moog servo-motors as generators with diode rectifiers and a 30kVA inverter proved to be feasible. The number of poles in the generators allow a gear ratio of 5:1 to be used without producing too high a voltage for the inverter, while keeping the generator torque within specifications.

The Moog generator configuration (with diode rectification and a 30kVA inverter) is recommended because it could be used to explore torque sharing uncertainty and staggered generator rectification to reduce ripple. Additionally, the Moog system with three 10kVA inverters would be an alternative system to test because of the uncertainties and cost saving potential of diode rectification.

With additional resources, this design project should continue by examining the availability of DC choppers for control in diode rectified systems. GTO systems and the option of using Bergey generators wound for 120Vac should also be investigated. After further analysis PE configurations, detailed design should commence.

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